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The maximum permissible interchannel crosstalk for imperceptible restriction of stereophonic stage width

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Summary

This Report discusses a study of the level of interchannel crosstalk at which stereophonic image movement away from the extreme left and right stage positions becomes imperceptible to the majority of observers.

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1. Introduction

In the design of a particular system of stereo-compatible quadraphonic encoding, certain combinations of input signals could in principle lead to the complete absence of one of the two output signals. This condition was considered undesirable as it could in turn lead to malfunction of certain types of quadraphonic decoding equipment. The introduction of deliberate crosstalk between the two output signals was therefore envisaged as a means of avoiding this condition. However, it was also considered essential to avoid impairing the stereophonic compatibility of the encoded signal by unnecessarily restricting the stereophonic stage width. Knowledge of the maximum "permissible" level of interchannel crosstalk, below which stereophonic image shifts away from the extreme left and right stage positions become imperceptible, are therefore required. Although the relationship between stereo image position and interchannel level ratio has been the subject of a number of investigations, there is a measure of disagreement between them in the prediction of permissible crosstalk. The work described in this Report was therefore undertaken specifically to examine this aspect of the stereophonic system.

For descriptive convenience the stereophonic channel carrying signal at full amplitude will be referred to as the "active" channel, and the loudspeaker associated with this channel will be called the "active" loudspeaker. The term "inactive" will similarly refer to the channel and loudspeaker carrying the low-level signal. Results are quoted in terms of the "maximum permissible crosstalk ratio" (C dB), where

$$C = 20 \log_{10} \frac{\text{(signal level in inactive channel)}}{\text{(signal level in active channel)}} \qquad (1)$$

the signal level in the inactive channel being such that with greater levels the sensation of extreme stage position (i.e. sound emanating from one or the other loudspeaker) is affected.

2. Previous work

A number of investigations, both theoretical and experimental, have been made of the relationship between the ratio of the signal levels emitted by each loudspeaker of a stereo pair and the apparent direction or "stage position" of the resulting sound image. Most of the results of such investigations, involving practical measurements of this relationship, are in reasonable agreement for image displacements from stage centre not exceeding about one-quarter of the stage width. Fig. 1 shows the results obtained over the portion of the stage extending from half-way between centre-front and extreme left or right and the extreme left or right position itself, where the differences between the various investigations are more pronounced. Not all the investigations included measurements at the extreme stage positions and in these cases the quoted results have been extrapolated (dotted lines in Fig. 1) by drawing a tangent to the curve where it terminates at the most extreme stage position measured. Because of the general tendency shown by most of the curves to increase in gradient as the extreme left or right stage position is approached, this process of extrapolation might be expected to give an under-estimate of the maximum permissible crosstalk ratio. Curves 1 – 5 inclusive are taken from Harwood's account[1a] of work published before or during 1962[2–7], while curve 11 shows Harwood's own results[1b] obtained at this time. Curve 8 shows results obtained by Harwood and Shorter[8a] during a specific investigation into the problem of interchannel crosstalk; this is cited as being in agreement with earlier work[9,10]. Fig. 1 also shows the experimental results obtained by Makita[11] (curves 6 and 7), Mertens[12] (curves 9 and 10) and Bower[13,14] (curves 12 – 14).

Clarke et al[4] Leakey[5], Makita[11] and Mertens[12] among others, have derived theoretical relationships between the ratio of the signal levels emitted by the two loudspeakers and the stage position of the resulting sound image. Although these relationships have been developed from a number of different initial premises, the conclusions reached are very similar. Using Leakey's formulation, if the loudspeakers subtend angles $\pm\ \theta$ at the observer's position, and if the sound image is perceived at an angle α relative to the stage centre, then for low frequencies

$$\tan\ \alpha = \frac{A - B}{A + B}\ \tan\ \theta \qquad (2)$$

while at high frequencies

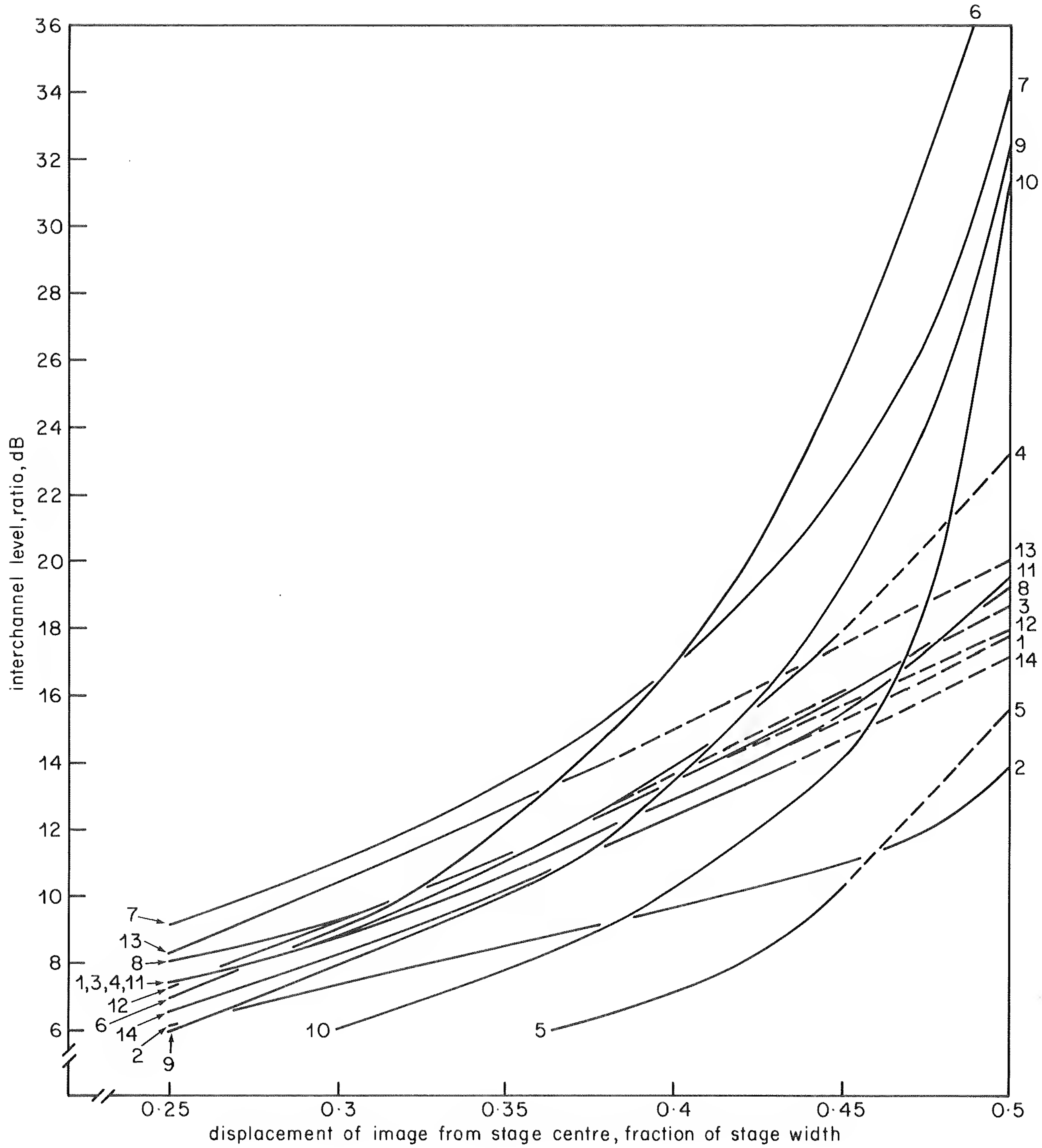

Fig. 1 - Relationships between image position and interchannel level ratio obtained by various workers.

1. De Boer 1940.
2. Brittain and Leakey 1956.
3. Leakey 1959.
4. Wendt 1960 (low frequencies)
5. Wendt 1960 (high frequencies)
6. Makita 1962 (low frequencies)
7. Makita 1962 (high frequencies)
8. Harwood and Shorter 1964
9. Mertens 1965 (low frequencies)
10. Mertens 1965 (high frequencies)
11. Harwood 1967
12. Bower 1975 (wideband)
13. Bower 1975 (low frequencies)
14. Bower 1975 (high frequencies)

dotted lines show extrapolation of experimental relationships

$$\sin\ \alpha = \frac{m^2\ (A^4 - B^4)}{(A^2 + m^2B^2)(m^2A^2 + B^2)} \sin\theta \qquad (3)$$

In Equations 2 and 3 A and B are respectively the greater and the lesser signal level emitted by each of the loudspeakers, and m is the attenuation, due to the presence of the observer's head, in the path between the left-hand loudspeaker and the right-hand ear, and vice versa. A value of m of 0.6 is quoted by Leakey. If $\alpha = \theta$ (i.e. the sound image coincides with one or other loudspeaker) then $B = 0$ from both Equations 2 and 3. Thus the only prediction of permissible interchannel crosstalk ratio that can be made theoretically is the self-evident one that the signal from the inactive speaker should be zero.

3. Experimental arrangements

Each observer was in turn seated in front of a standard stereophonic listening arrangement, in which the two loudspeakers and the observer were situated at the apices of an equilateral triangle of side 10ft (3m). The same signal could be supplied to each loudspeaker by way of a calibrated attenuator and a switch (Fig. 2). The observer was asked to set the attenuator in the inactive channel to the smallest value (i.e. least attenuation) for which operation of the switch in series with this attenuator caused no perceptible movement of the sound image away from the active loudspeaker. Adjustment of the attenuator in the active channel was also permitted to obtain a listening level acceptable to the observer. This process was carried out in turn with the left-hand and right-hand channels as active, the difference (in decibels) of the attenuator settings in the active and inactive channels being noted in each case.

The tests were carried out in a listening room of volume about 250 ft^3 (70m^3) having a reverberation time of 0.35 seconds. Two series of tests were carried out: first with in-phase signals supplied to the two loudspeakers, and again with the two signals differing in phase by 30°. This latter condition was used to simulate the outputs of the quadraphonic encoder. Seven experienced observers took part in each of the tests but most returned assessments for two types of programme material ("off-air" speech and music): twelve observations were made with the stereo image at each extreme state position in the case of the "in-phase" tests, and thirteen observations at each stage position in the case of the "30° phase-shift" tests.

4. Results of tests

Tables 1 and 2 show the mean maximum permissible crosstalk ratios, together with the standard deviations of the results and the number of observations made, for the cases in which the signals supplied to the two loudspeakers were in phase and shifted in phase by 30° respectively. In each case the difference in mean value obtained for images on the left and right of the sound stage have been tested for significance using the method outlined in the Appendix to this Report. Since in both cases this difference was not significant, the results for stage-left and stage-right images have been averaged and are shown in Table 3. The difference in these mean values obtained for in-phase and 30° phase-shifted signals was also found not to be significant, and an average has again been taken to give an overall mean value of maximum permissible crosstalk ratio, as shown in Table 4.

In the present context it is not the mean value

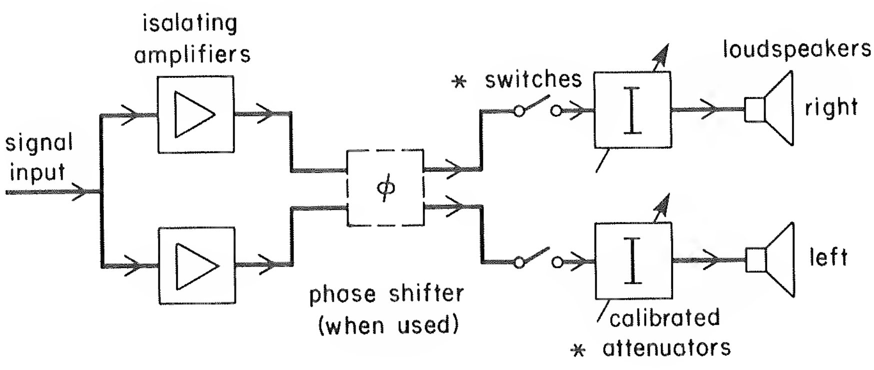

Fig. 2 - Equipment arrangement
*operated by observer

Table 1, Mean Crosstalk ratios, distributions about mean value and test of significance: in-phase signals

Experimental Condition	Experimental Results			Test of Significance of the Difference between the two mean values (see Appendix, Equation 9)		
	Maximum Permissible Crosstalk ratio (dB)		Number of Observations			
	Mean	Standard Deviation		T'_0	$t_{0.05}$	Significant Difference?
Left Image	−18.83	1.80	12	1.30	2.07	No
Right Image	−17.75	2.09	12			

Table 2, Mean Crosstalk ratios, distributions about mean value, and test of significance: 30° phase-shifted signals

Experimental Condition	Experimental Results			Test of Significance of the Difference between the two mean values (see Appendix, Equation 9)		
	Maximum Permissible Crosstalk ratio (dB)		Number of Observations			
	Mean	Standard Deviation		T'_0	$t_{0.05}$	Significant Difference?
Left Image	−18.92	1.71	13	0.30	2.06	No
Right Image	−18.69	2.06	13			

Table 3, Mean Crosstalk ratios, distributions about mean value, and test of significance: averages of left and right images

Experimental Condition	Experimental Results			Test of Significance of the Difference between the two mean values (see Appendix, Equation 9)		
	Maximum Permissible Crosstalk ratio (dB)		Number of Observations			
	Mean	Standard Deviation		T'_0	$t_{0.05}$	Significant Difference?
Left Image	−18.29	1.95	24	1.66	2.01	No
Right Image	−18.80	1.89	26			

of maximum permissible crosstalk that is of significance, as statistically this only indicates the ratio for which half the observations indicate an imperceptible effect of the inactive channel signal on image position. A crosstalk ratio which indicated an imperceptible effect of the inactive channel in, say, 95% of all cases would be more meaningful as it would provide a criterion of imperceptibility to all but the most sensitive observer. The derivation of such value is discussed in the Appendix. Inserting the mean and standard deviation values shown in Table 4 into Equation 11 (Appendix) leads to the result that the limiting value of maximum permissible crosstalk ratio, such that the restricting of stereophonic stage width will be imperceptible with a probability of 0.95, is −21.6 dB or −22 dB to the nearest whole number.

Table 4, Mean Crosstalk, distribution about mean value and confidence limit

Maximum permissible crosstalk ratio (dB): average of left and right active channels, and of in-phase and 30° phase shift signals		Number of Observations	Confidence limit (see Appendix Equation 6)
Mean	Standard Deviation		
−18.5	1.9	50	± 0.6

5. Discussion

Inspection of Fig. 1 shows that the values of maximum permissible crosstalk ratio indicated by the results of Leakey[5] (curve 3), Harwood and Shorter[8] (curve 8) and Bower[13] (curve 12 for wide-bandwidth signals) agree with the mean result obtained in the present investigation (see Section 4, Table 4). The results obtained by De Boer[2] and Harwood[1] are only just outside the confidence limit shown in Table 4. Of these results, only those obtained by Harwood and Harwood and Shorter do not involve extrapolation. Taking this into account, and also the fact that all the experimental results will be subject to their own confidence limits of roughly speaking the same order of magnitude as obtained in the present work, it may be concluded that the mean value of maximum permissible crosstalk ratio obtained in the present work is in agreement with the results obtained by the above-named workers. It may also be seen that the results of Makita[11] and Mertens[12] are in substantial disagreement with the present work, although there is no obvious difference in their experimental techniques that would account for such a difference.

It is interesting to compare the limiting value of maximum permissible crosstalk ratio (which nominally refers to 95% of all observers) obtained during the present work (−21.6 dB) with corresponding values deduced from the results given by Harwood and Shorter[8] and Harwood[1]. Harwood and Shorter quote a value of −19.2 dB[8a] for the "calculated position of edge of image for minimum perceptible crosstalk" and show[8b] that a further 5.5 dB decrease in crosstalk is required before the number of observations of perceptible crosstalk is reduced to 5% of the total. These results indicate a limiting crosstalk ratio of −24.7 dB. Harwood obtained a value[1b] of −20.6 dB ± 1.4 dB for the attenuation required in the inactive channel for a fully displaced stereophonic image. Using Equation 11 (Appendix) and taking the 1.4 dB limits as referring to the standard deviation of the observed results, leads to a limiting crosstalk ratio of −22.9 dB. These results are compared in Table 5, from which it may be seen that reasonable agreement exists between the limiting crosstalk ratio values deduced from the present and this earlier work.

The experimentally-derived maximum permissible crosstalk ratio values may be inserted into Equations 2 and 3 (Section 2) to give the theoretical "minimum perceptible" image shifts away from the extreme stage positions which are involved (see Table 6). Strictly speaking this process is not valid, since the crosstalk ratio values refer to wide bandwidth signals while Equations 2 and 3 refer to low and high frequency signals respectively. However, Bower's results[14] show that the image position obtained for a wide bandwidth signal, for a given interchannel level ratio, is approximately the mean of the positions obtained for low and high frequency signals (compare curve 12 with curves

Table 5, Comparison of limiting crosstalk ratios obtained from the results of different workers

Source	Maximum permissible crosstalk ratio (dB)		
	Mean Value	Correction	Limiting Value
Present Work	−18.5	−3.1	−21.6
Harwood and Shorter	−19.2	−5.5	−24.7
Harwood	−20.6	−2.3	−22.9

Table 6, Image shifts away from stage extremities

Crosstalk Ratio (dB)	Image shifts away from extreme stage position (fraction of stage width)		
	Low Frequencies (Equation 2)	High Frequencies (Equation 3)	Mean
−18.5 (mean value)	0.092	0.024	0.058
−21.6 (limiting value)	0.066	0.012	0.039

13 and 14 in Fig. 1). Averaging the results obtained from Equations 2 and 3 gives the image shifts shown in the right-hand column of Table 6. These values may be compared with the average perceived image width of 0.22 times the stage width obtained by Harwood[1c] for images at the extreme stage positions. In these terms the mean and limiting crosstalk ratio values imply minimum perceptible image shifts of 0.26 and 0.18 times the image width respectively.

It may be also noted that Bower's results[13,14] obtained using zero and 34° interchannel phase-shift show that image position is only very slightly affected by this amount of phase shift. This is consistent with the results of the present work that the effect of a 30° interchannel phase shift is insignificant.

6. Conclusions

In a stereophonic sound system, the sensation of extreme left or right image position is preserved for the majority of listeners if the signal level in the unused or "inactive" channel is attenuated by at least 21.6 dB (say 22 dB) relative to the signal in the used or active channel. This is equivalent to a shift in image position, away from the extreme stage position, of approximately one-fifth of the image width. The result applies equally if a phase-shift of 30° exists between the signals in the two channels.

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Appendix

STATISTICAL TREATMENT OF RESULTS

In order to evaluate the significance of mean values of results, the results returned by individual observers may be regarded as random samples of a large population of such results. Let X be a variable which is normally distributed about a mean value μ with standard deviation σ. Let $\bar{X}$ and S be sample estimates of μ and σ respectively, based on a random sample of n values of X. Then it can be shown[15a] that the variable T has the Student –t distribution with $(n - 1)$ degrees of freedom, where

$$T = \frac{(\bar{X} - \mu)(n - 1)^{1/2}}{S} \tag{4}$$

If t_p represents the value of T such that the probability is p that $|T| \geqslant t_p$ (i.e. the "two-tailed" probability value), then the probability is $(1 - p)$ that $|T| < t_p$. Thus

$$\left| \frac{(X - \mu)(n - 1)^{1/2}}{S} \right| < t_p \tag{5}$$

or

$$\bar{X} - \frac{t_p . S}{(n - 1)^{1/2}} < \mu < \bar{X} + \frac{t_p . S}{(n - 1)^{1/2}} \tag{6}$$

Now, consider the case where two variables X and Y are each normally distributed about mean values μ_x and μ_y with the same standard deviation σ. Let $\bar{X}$, $\bar{Y}$, S_x, S_y be sample estimates of the means and standard deviation, based on random samples of n_x, n_y values of X and Y respectively. Then the variable T' has the Student –t distribution with $(n_x + n_y - 2)$ degrees of freedom where

$$T' = \left[(\bar{X} - \bar{Y}) - (\mu_x - \mu_y)\right] \left[\frac{(n_x n_y (n_x + n_y - 2)}{(n_x + n_y)(n_x S_x^2 + n_y S_y^2)}\right]^{1/2} \tag{7}$$

To test the hypothesis that the mean values of the variables X and Y are equal, with probability $(1 - p)$, let $(\mu_x - \mu_y) = 0$ in Equation 7 and let the corresponding value of T' be T'_o. Then

$$T'_o = (\bar{X} - \bar{Y}) \left[\frac{n_x n_y (n_x + n_y - 2)}{(n_x + n_y)(n_x S_x^2 + n_y S_y^2)}\right]^{1/2} \tag{8}$$

Now test to see whether $T'_o < t_p$, where t_p is the value of the Student –t variable for a two-tailed probability of p and $(n_x + n_y - 2)$ degrees of freedom. If this test is satisfied then the initial hypothesis is proved, and $\mu_x = \mu_y$ with probability $(1 - p)$.

It is conventional to take $p = 0.05$ as a criterion for judging whether an event is or is not statistically significant, the argument being that if there is only a one in twenty likelihood of the event occurring purely by chance, then when the event does occur it is very likely to have been caused by a change in the parameters which govern the events under consideration. Thus, two mean values are not considered to differ significantly if

$$T'_o < t_{0.05} \tag{9}$$

where T'_o is obtained from Equation 8, and $t_{0.05}$ is the value of the Student –t variable for a two-tailed probability of 0.05 and for $(n_x + n_y - 2)$ degrees of freedom. Furthermore, in the case of the confidence limits given by Equation 6 the appropriate value for t_p is also for $p = 0.05$ (two-tailed) but for $(n - 1)$ degrees of freedom. Values of the Student –t variable are given in most standard works on statistics[15b,16].

Up to now the results returned by individual observers have been regarded as random samples of a large population. This has enabled conclusions to be drawn about the confidence limits that can be placed on a single mean value, and the significance of the difference between two mean values. In fact, the scatter of the results obtained by different observers is due, presumably, to the differing opinions of those observers or in other words the differing sensitivity of the observers to the effect under investigation. If a mean value $(\bar{X})$ of the results is taken, then it may be expected that half the observers will have returned results above this mean value and half below it. It is however, possible to derive a "limiting" value X_{lim} such that there is a certain probability p that an observer will return a result on one side of this value and another probability $(1 - p)$ that the result will be on the other side of this value. As before, it is conventional to take $p = 0.05$; in this case it can be shown[17] that

$$X_{lim} = \bar{X}\,(1 \pm 1.64S) \tag{10}$$

where S is the standard deviation of the individual results. The sign within the bracketed term in Equation 10 is determined by the purpose for which the limiting value is required. If, as in the case discussed in Section 4 of this Report, it is required to give a more stringent limit than is provided by the mean value, and if, as is also the present case, an increase in the value of $|X|$ implies an increase in such stringency, then the positive sign is taken and

$$X_{\text{lim}} = \bar{X} \ (1 + 1.64\,S) \tag{11}$$

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